Parton Distributions and New Physics Searches: the Drell-Yan Forward-Backward Asymmetry as a Case Study

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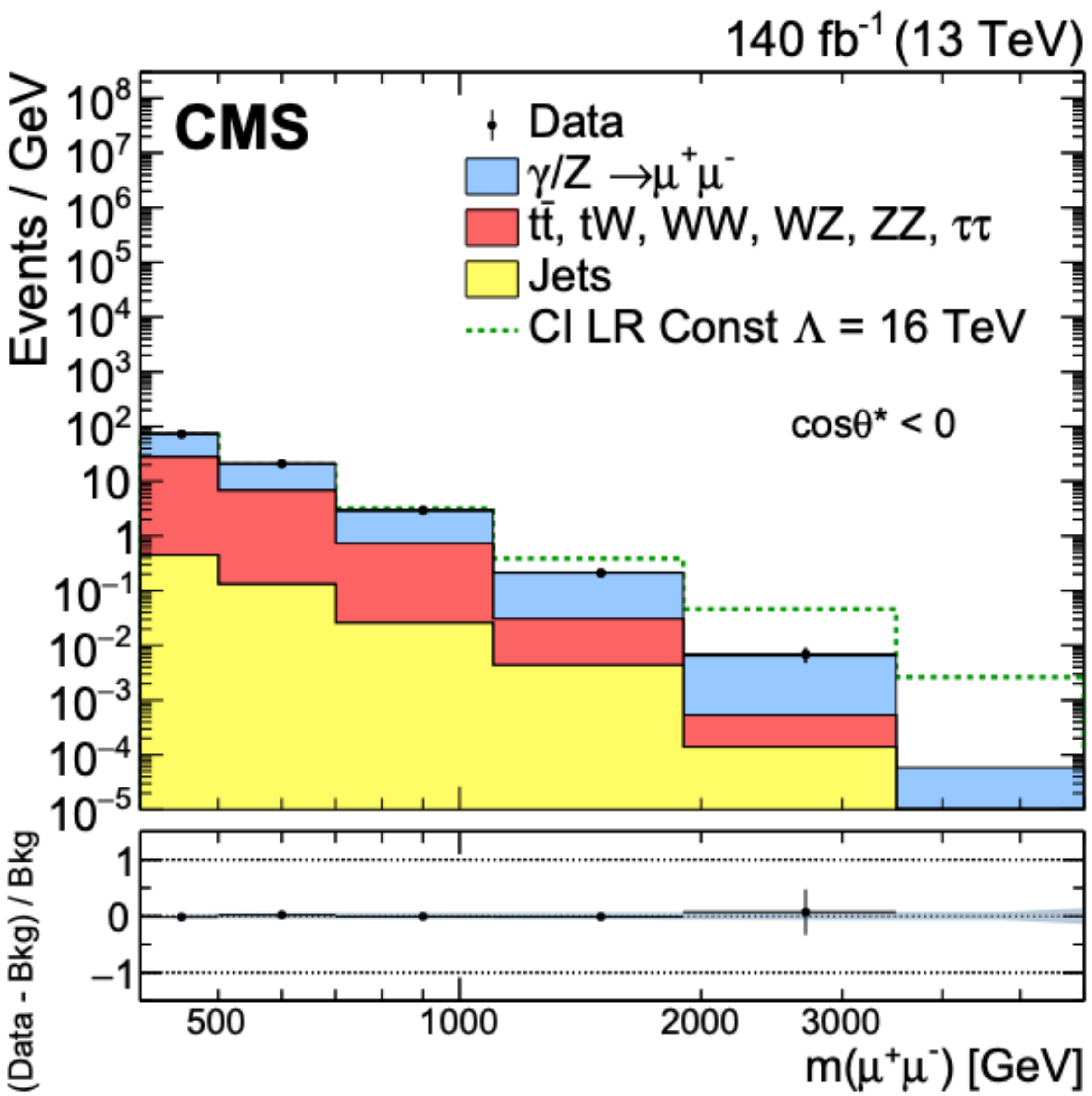
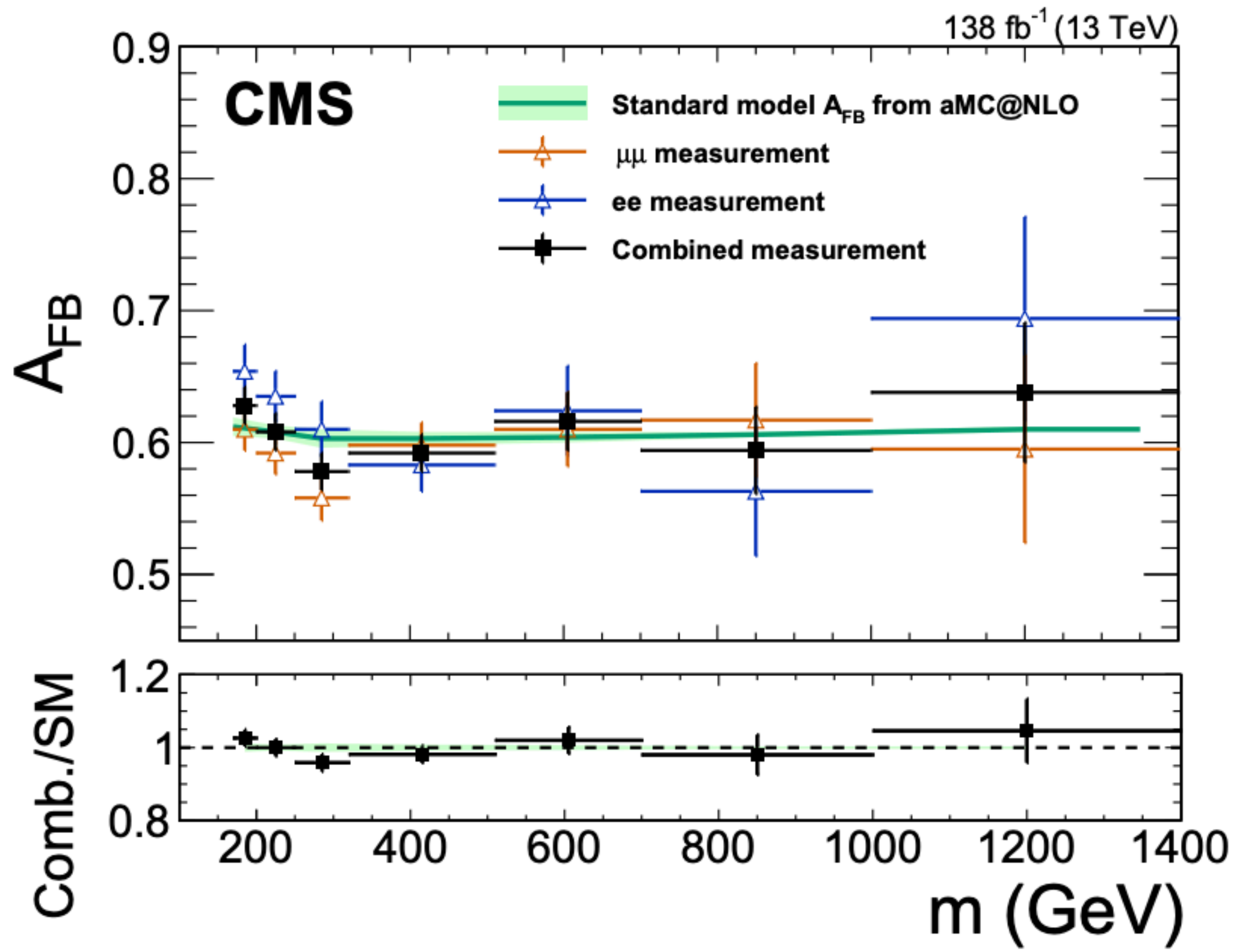
BSM Searches with High-Mass Drell-Yan

- High-mass neutral-current Drell-Yan is a very sensitive processes for BSM searches
- **Resonant** and **EFT new physics** can be probed with the invariant mass distributions, while **off-shell interference** (e.g. Z' boson) one can use the **Forward-Backward asymmetry**





- Current understanding of **large-*x* PDFs**: robust enough for present and future searches in DY?

Neutral-Current Drell-Yan

- At leading order, the **triple differential cross-section** in neutral-current Drell-Yan production is

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar{\ell}}\,\mathrm{d}y_{\ell\bar{\ell}}\,\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar{\ell}}s}\Bigg((1+\cos^2(\theta^*))\sum_q S_q\left[f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}})+f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\right]$$
$$+\cos\theta^*\sum_q A_q\,\mathrm{sign}(y_{\ell\bar{\ell}})\left[f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}})-f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\right]\Bigg)$$

dilepton invariant mass

dilepton rapidity

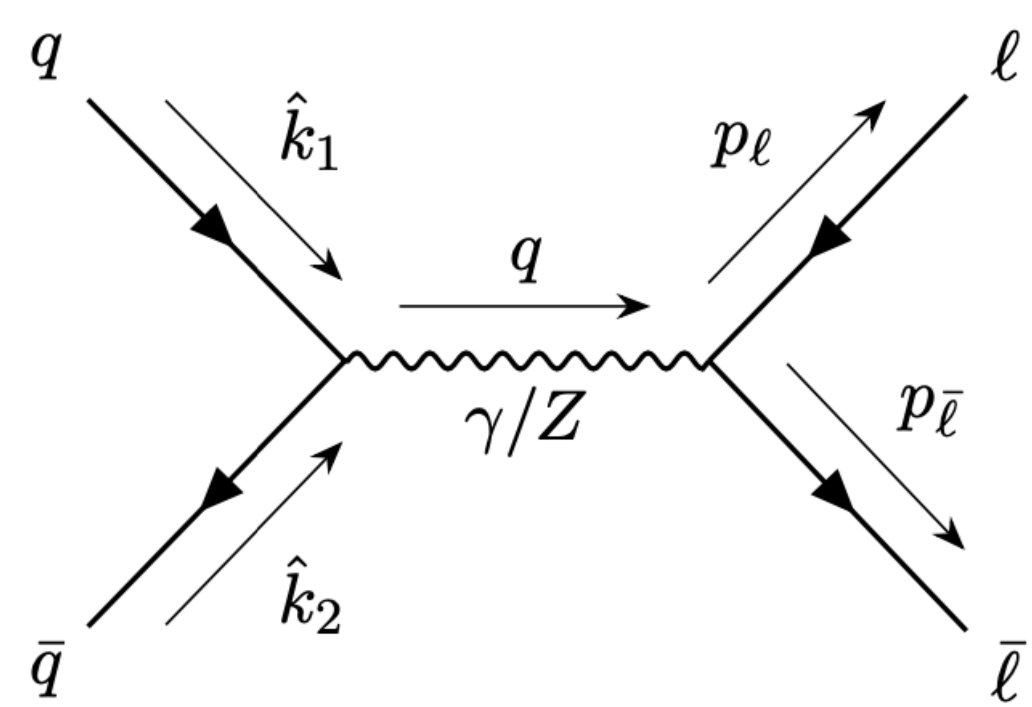
Collins-Soper angle

$$x_1 = \frac{m_{\ell\bar{\ell}}}{\sqrt{s}}\exp(y_{\ell\bar{\ell}})\,, \quad x_2 = \frac{m_{\ell\bar{\ell}}}{\sqrt{s}}\exp(-y_{\ell\bar{\ell}})$$

$$S_q = e_l^2 e_q^2 + P_{\gamma Z}\cdot e_l v_l e_q v_q + P_{ZZ}\cdot(v_l^2+a_l^2)(v_q^2+a_q^2)$$
$$A_q = P_{\gamma Z}\cdot 2e_l a_l e_q a_q + P_{ZZ}\cdot 8v_l a_l v_q a_q\,,$$

$$P_{\gamma Z}(m_{\ell\bar{\ell}}) = \frac{2m^2_{\ell\bar{\ell}}(m^2_{\ell\bar{\ell}}-m_Z^2)}{\sin^2(\theta_W)\cos^2(\theta_W)\left[(m^2_{\ell\bar{\ell}}-m_Z^2)^2+\Gamma_Z^2 m_Z^2\right]}$$

$$P_{ZZ}(m_{\ell\bar{\ell}}) = \frac{m^4_{\ell\bar{\ell}}}{\sin^4(\theta_W)\cos^4(\theta_W)\left[(m^2_{\ell\bar{\ell}}-m_Z^2)^2+\Gamma_Z^2 m_Z^2\right]}$$



Neutral-Current Drell-Yan

- Express in terms of **symmetric** and **antisymmetric** parton luminosities

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar{\ell}}\,\mathrm{d}y_{\ell\bar{\ell}}\,\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar{\ell}}s}\left((1+\cos^2(\theta^*))\sum_q S_q\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) + \cos\theta^*\sum_q A_q\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})\right)$$

dilepton invariant mass

dilepton rapidity

Collins-Soper angle

symmetric effective coupling

antisymmetric effective coupling

$$\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv f_q(x_1,m_{\ell\bar{\ell}}^2)f_{\bar{q}}(x_2,m_{\ell\bar{\ell}}^2) + f_q(x_2,m_{\ell\bar{\ell}}^2)f_{\bar{q}}(x_1,m_{\ell\bar{\ell}}^2)\,,$$
$$\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv \mathrm{sign}(y_{\ell\bar{\ell}})\left[f_q(x_1,m_{\ell\bar{\ell}}^2)f_{\bar{q}}(x_2,m_{\ell\bar{\ell}}^2) - f_q(x_2,m_{\ell\bar{\ell}}^2)f_{\bar{q}}(x_1,m_{\ell\bar{\ell}}^2)\right]$$

invariant under $x_1 \leftrightarrow x_2$

- The Collins-Soper angle is defined in the **hadronic CoM frame**

$$\cos\theta^* = \mathrm{sign}(y_{\ell\bar{\ell}})\cos\theta\,,$$
$$\cos\theta \equiv \frac{p_\ell^+ p_{\bar{\ell}}^- - p_\ell^- p_{\bar{\ell}}^+}{m_{\ell\bar{\ell}}\sqrt{m_{\ell\bar{\ell}}^2 + p_{\mathrm{T},\ell\bar{\ell}}^2}}, \quad p^\pm = p^0 \pm p^3$$

coincides with the lepton scattering angle in the **partonic CoM frame**

Neutral-Current Drell-Yan

- Express in terms of **symmetric** and **antisymmetric** parton luminosities

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar{\ell}}\,\mathrm{d}y_{\ell\bar{\ell}}\,\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar{\ell}}s}\left((1+\cos^2(\theta^*))\sum_q S_q\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) + \cos\theta^*\sum_q A_q\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})\right)$$

dilepton invariant mass

dilepton rapidity

Collins-Soper angle

symmetric effective coupling

antisymmetric effective coupling

even under

$\cos(\theta^*) \to -\cos(\theta^*)$

odd under

$\cos(\theta^*) \to -\cos(\theta^*)$

- Combination of **symmetric** and **antisymmetric contributions** in the Collins-Soper angle
- A **forward-backward (FB) asymmetry** arises when antisymmetric lumi is non-zero

$$\left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\mathrm{FB}} = \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\cos\theta^*} - \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{-\cos\theta^*}$$

$$\left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\mathrm{FB}} = \frac{2\pi\alpha^2\cos(\theta^*)}{3m_{\ell\bar{\ell}}s}\sum_q A_q\mathscr{L}_{A,q}$$

At LO, properties of forward-backward asymmetry dictated by antisymmetric parton luminosity

Neutral-Current Drell-Yan

- **One-dimensional distributions** obtained from integrating the 3D ones

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_{\ell\bar\ell}} = \int_{m_{\ell\bar\ell}^{\min}}^{\sqrt{s}} \mathrm{d}m_{\ell\bar\ell} \int_{-1}^{1} \mathrm{d}\cos\theta^* \, \frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar\ell}\,\mathrm{d}y_{\ell\bar\ell}\,\mathrm{d}\cos\theta^*}$$

Used frequently in global PDF fits

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \int_{m_{\ell\bar\ell}^{\min}}^{\sqrt{s}} \mathrm{d}m_{\ell\bar\ell} \int_{\ln(m_{\ell\bar\ell}/\sqrt{s})}^{\ln(\sqrt{s}/m_{\ell\bar\ell})} \mathrm{d}y_{\ell\bar\ell} \, \frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar\ell}\,\mathrm{d}y_{\ell\bar\ell}\,\mathrm{d}\cos\theta^*}$$

Used to extract EW parameters and also proposed for PDF fits

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = (1+\cos^2\theta^*)\sum_q g_{S,q} + \cos\theta^* \sum_q g_{A,q}$$

$$g_{A,q} = \frac{\pi\alpha^2}{3s} \int_{m_{\ell\bar\ell}^{\min}}^{\sqrt{s}} \frac{\mathrm{d}m_{\ell\bar\ell}}{m_{\ell\bar\ell}} A_q(m_{\ell\bar\ell}) \int_{\ln(m_{\ell\bar\ell}/\sqrt{s})}^{\ln(\sqrt{s}/m_{\ell\bar\ell})} \mathrm{d}y_{\ell\bar\ell}\, \mathcal{L}_{A,q}(m_{\ell\bar\ell}, y_{\ell\bar\ell})$$

- All PDF dependence into the **coefficients $g_{A,q}$ and $g_{,q}$**, dependence in CS angle ``trivial”

Forward-Backward asymmetry

- The forward-backward asymmetry is defined to be proportional to the **terms odd in CS angle**:

$$A_{\rm fb}(\cos\theta^*) \equiv \frac{\frac{{\rm d}\sigma}{{\rm d}\cos\theta^*}(\cos\theta^*) - \frac{{\rm d}\sigma}{{\rm d}\cos\theta^*}(-\cos\theta^*)}{\frac{{\rm d}\sigma}{{\rm d}\cos\theta^*}(\cos\theta^*) + \frac{{\rm d}\sigma}{{\rm d}\cos\theta^*}(-\cos\theta^*)}\,, \qquad \cos\theta^* > 0\,,$$

- At LO the dependence on the CS angle **factorises** from the PDF dependence

$$A_{\rm fb}(\cos\theta^*) = \underbrace{\frac{\cos\theta^*}{(1+\cos^2(\theta^*))}}_{\textit{PDF-independent}}\;\underbrace{\frac{\sum_q g_{A,q}}{\sum_{q'} g_{S,q'}}}_{\textit{PDF-dependent}}\,, \qquad \cos\theta^* > 0$$

- Hence, to understand the **high-mass behaviour of A_{FB}** it suffices to consider that of the antisymmetric PDF luminosities

$$g_{A,q} = \frac{\pi\alpha^2}{3s}\int_{m_{\ell\bar\ell}^{\rm min}}^{\sqrt{s}} \frac{{\rm d}m_{\ell\bar\ell}}{m_{\ell\bar\ell}} A_q(m_{\ell\bar\ell}) \int_{\ln(m_{\ell\bar\ell}/\sqrt{s})}^{\ln(\sqrt{s}/m_{\ell\bar\ell})} {\rm d}y_{\ell\bar\ell}\,\mathcal{L}_{A,q}(m_{\ell\bar\ell}, y_{\ell\bar\ell})$$

The following quantitative discussion is unaffected by higher-order QCD and EW corrections

We will then carry out LHC phenomenology using NLO QCD+EW calculations

Neutral-Current Drell-Yan

- The antisymmetric parton luminosities dictate the **behaviour of the FB asymmetry**

- They can also be expressed in terms of **sea-like** and **valence-like** PDF combinations

$$\mathcal{L}_{S,q}(m_{\ell\bar{\ell}}, y_{\ell\bar{\ell}}) = \frac{1}{2}\left(f_q^+(x_1, m_{\ell\bar{\ell}}^2) f_q^+(x_2, m_{\ell\bar{\ell}}^2) - f_q^-(x_2, m_{\ell\bar{\ell}}^2) f_q^-(x_1, m_{\ell\bar{\ell}}^2)\right)$$

$$\mathcal{L}_{A,q}(m_{\ell\bar{\ell}}, y_{\ell\bar{\ell}}) = \frac{\mathrm{sign}(y_{\ell\bar{\ell}})}{2}\left(f_q^-(x_1, m_{\ell\bar{\ell}}^2) f_q^+(x_2, m_{\ell\bar{\ell}}^2) - f_q^-(x_2, m_{\ell\bar{\ell}}^2) f_q^+(x_1, m_{\ell\bar{\ell}}^2)\right)$$

$$f_q^{\pm}(x, Q) = f_q(x, Q) \pm f_{\bar{q}}(x, Q)$$

- In the ***Z*-peak region**, hierarchy of momentum fractions: $x_1 \gg x_2$

$$\mathcal{L}_{A,u}(y_{\ell\bar{\ell}}, m_{\ell\bar{\ell}}) \approx \frac{1}{2} f_u^-(x_1, m_{\ell\bar{\ell}}^2) f_u^+(x_2, m_{\ell\bar{\ell}}^2)$$

$$x_1 = \frac{m_{\ell\bar{\ell}}}{\sqrt{s}} \exp(y_{\ell\bar{\ell}})\,, \quad x_2 = \frac{m_{\ell\bar{\ell}}}{\sqrt{s}} \exp(-y_{\ell\bar{\ell}})$$

- Hence measurements of the FB asymmetry on the Z-peak can constrain **valence quark PDFs**

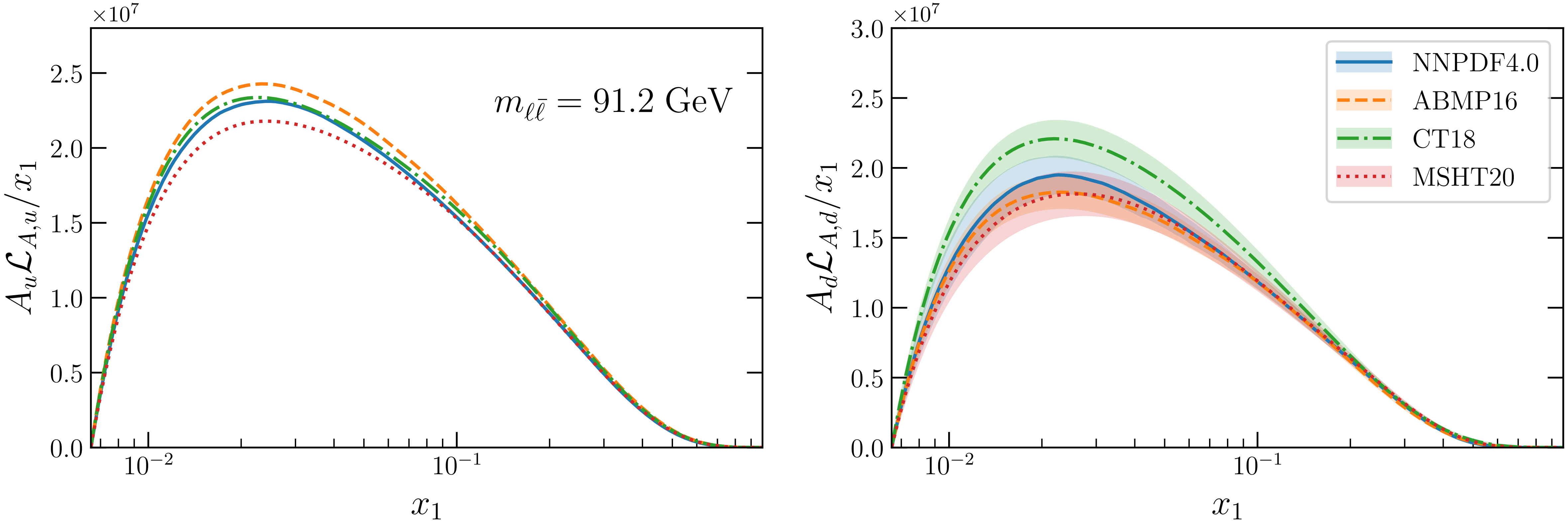
in addition, also the weak mixing angle can be measured

*The integral over valence quark PDFs is a positive quantity (sum rules), it then follows that the forward-backward asymmetry is **positive-definite in the Standard Model?***

very attractive feature for robust BSM searches!

Antisymmetric PDF luminosities

- At the **Z-peak region** we probe **valence PDFs:** antisymmetric parton lumis behave valence-like



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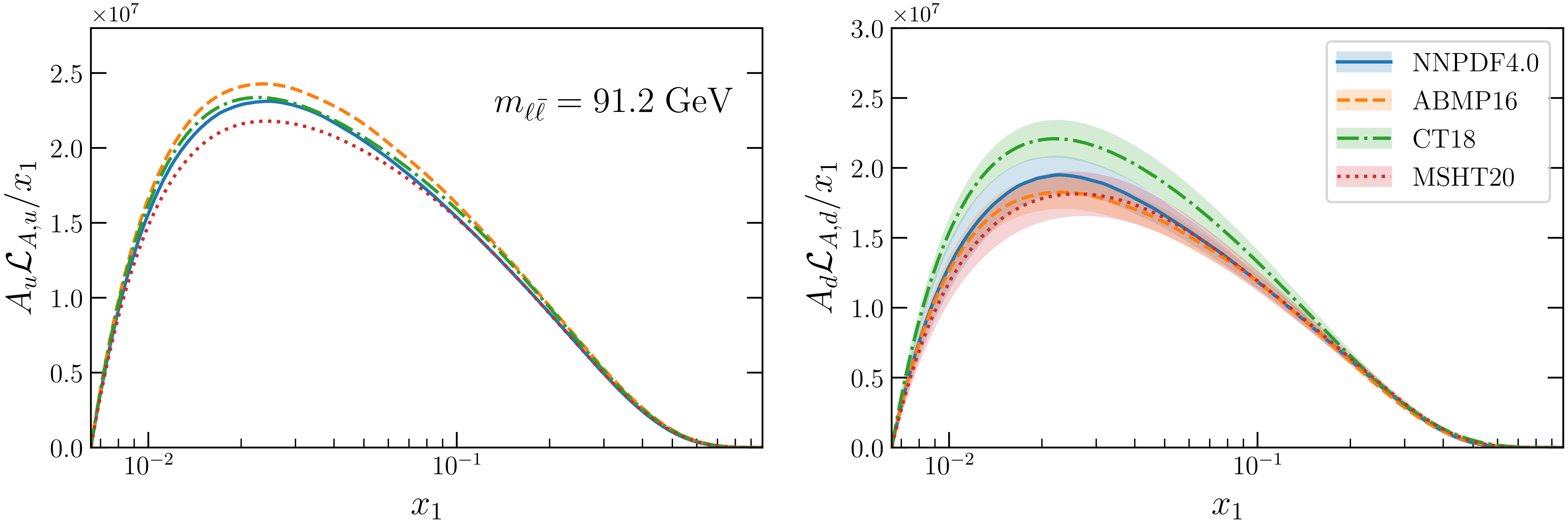
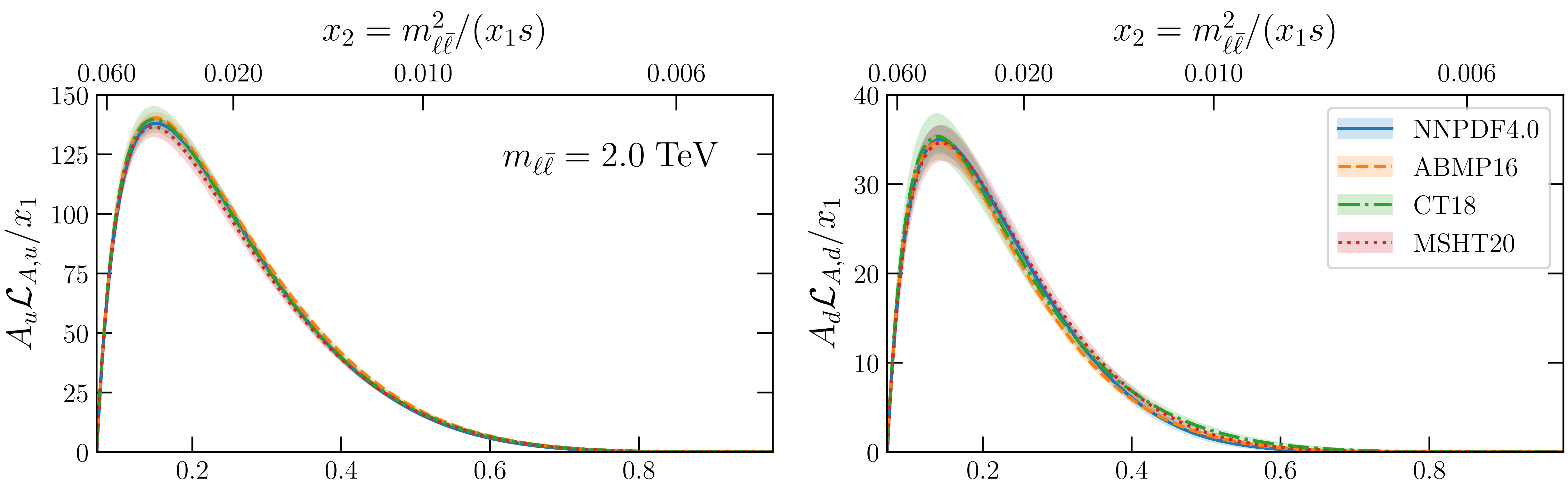


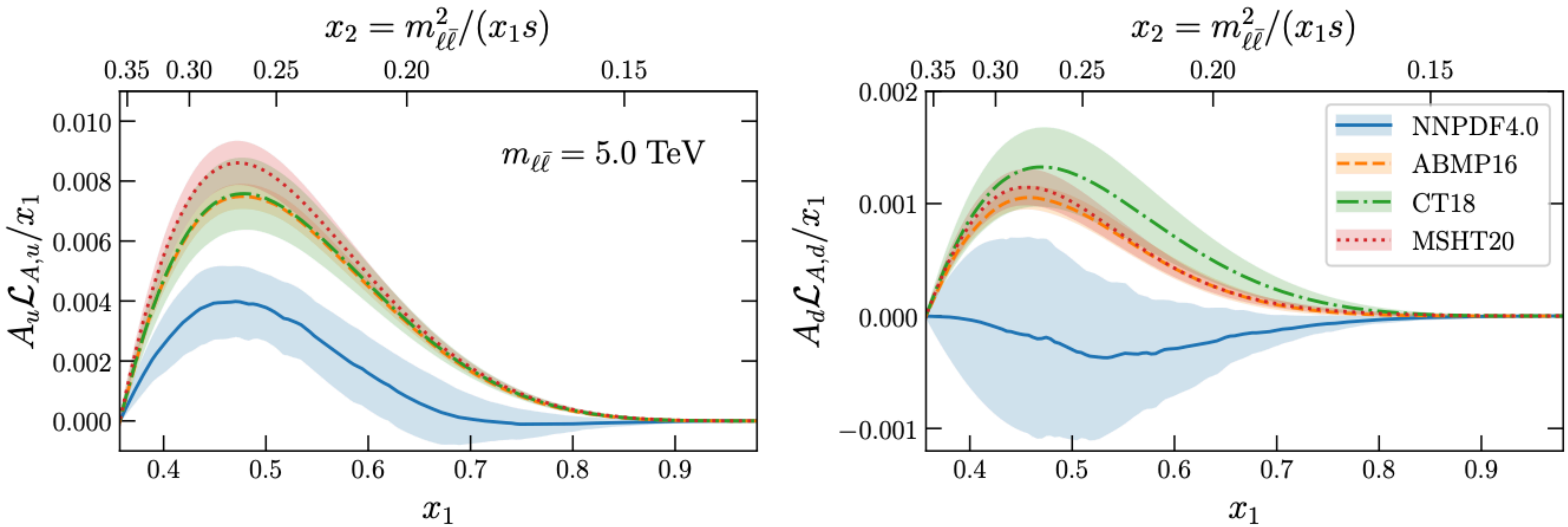
- Same as we go to **2 TeV**, and note good agreement between PDF fits



extrapolation to yet higher invariant masses trivial?

Antisymmetric PDF luminosities

- At **5 TeV**, very different behaviour in NNPDF4.0: ***A$_{FB}$*** may not be positive definite after all



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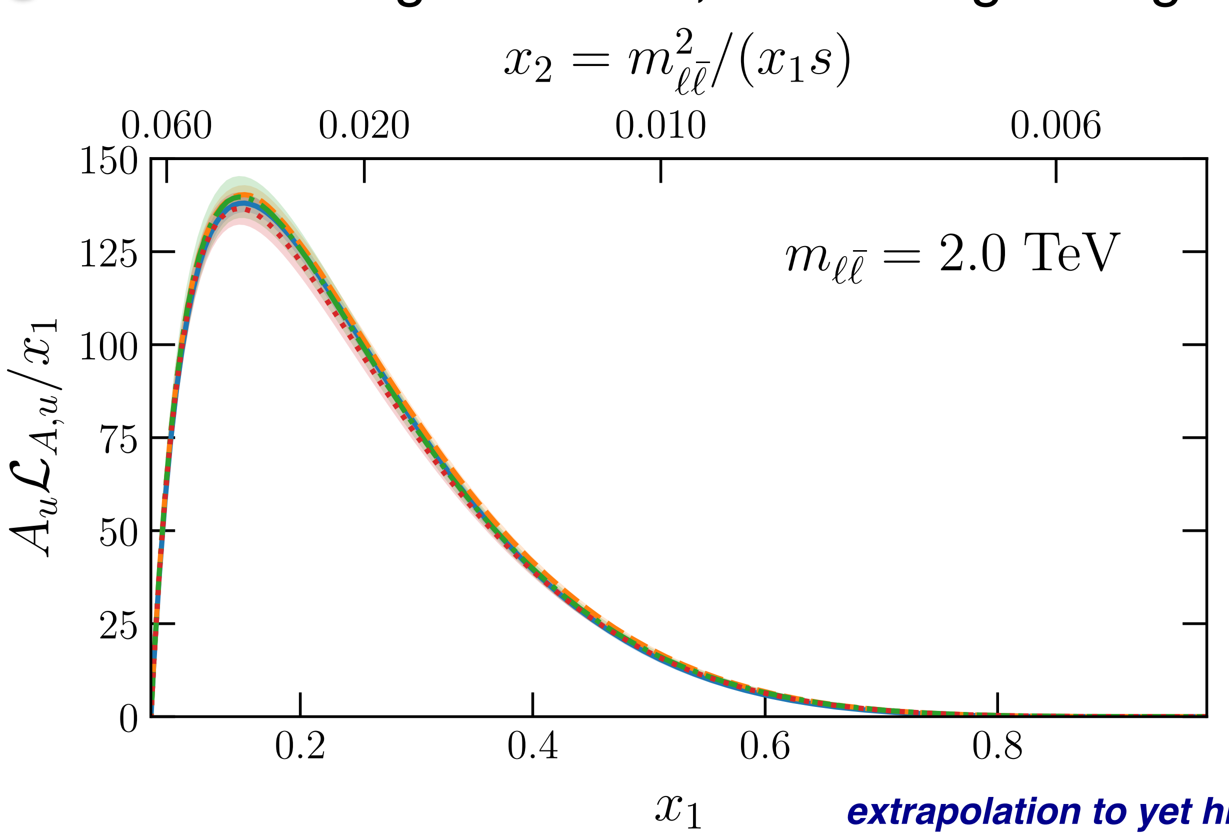
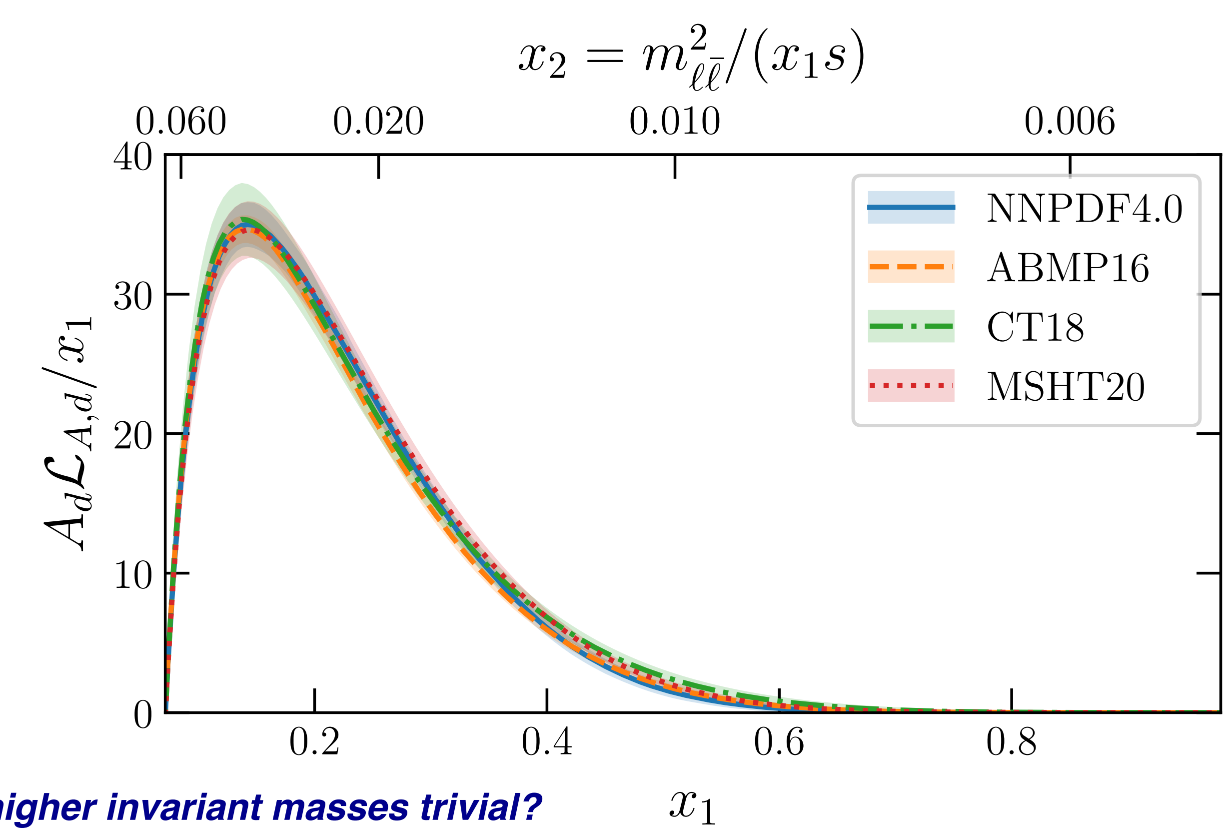
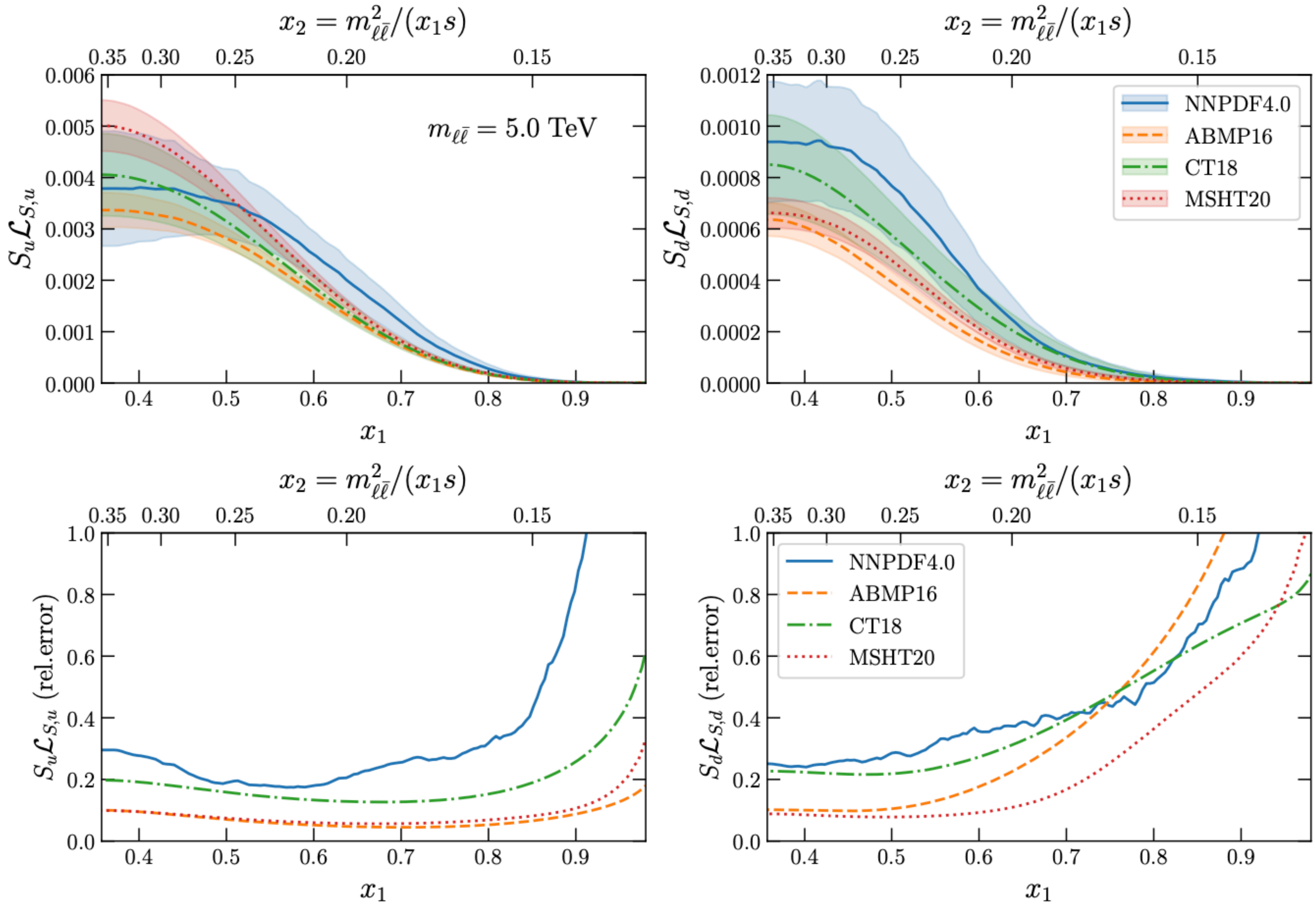




extrapolation to yet higher invariant masses trivial?

Symmetric PDF luminosities

- On the other hand, symmetric parton luminosities are in **good qualitative agreement** even at very high masses, with **NNPDF4.0** displaying the largest PDF uncertainties



How can this behaviour be explained?

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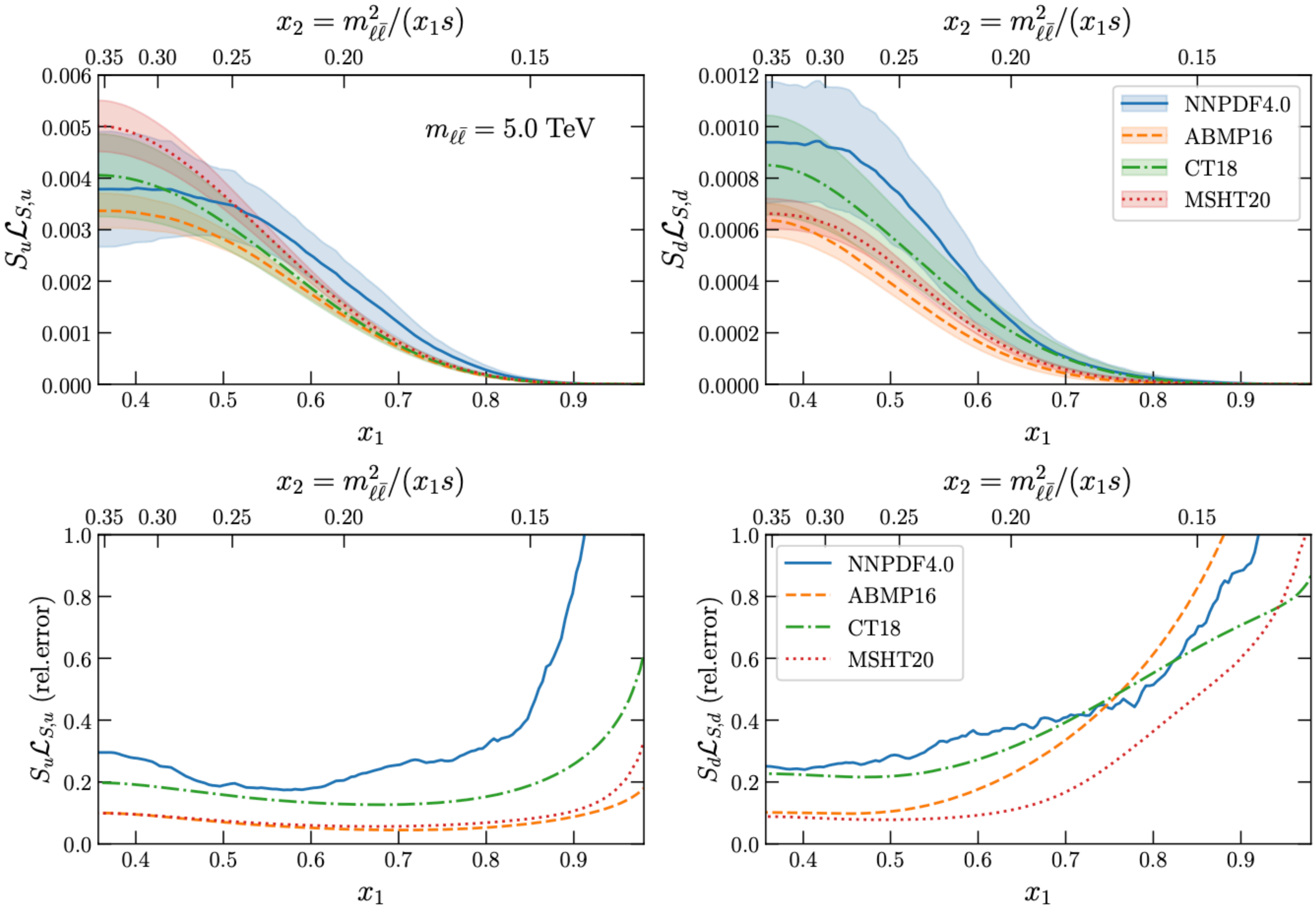


How can this behaviour be explained?

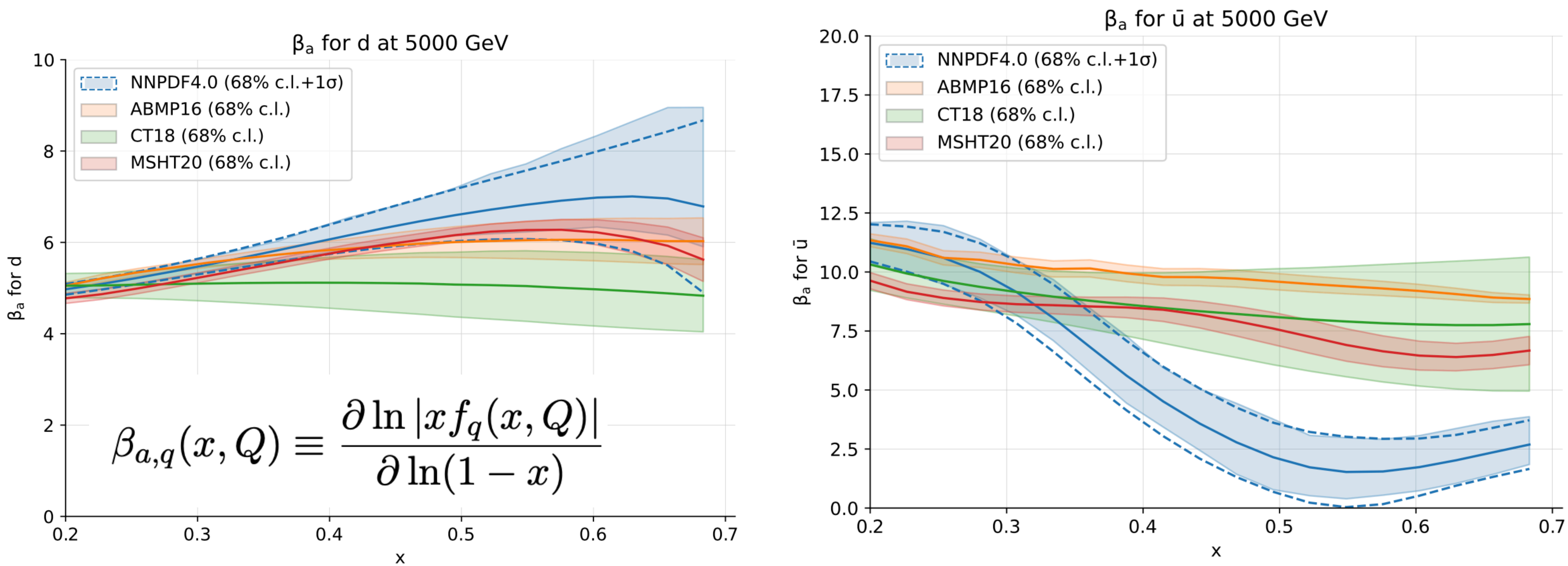
Positive or negative asymmetry?

- The general condition on the **sign of the forward-backward asymmetry** is given at LO by

$$\mathrm{sign}\left[\mathcal{L}_{A,q}\right] = \mathrm{sign}\left[\frac{f_q^+(x_2)}{f_q^+(x_1)} - \frac{f_q^-(x_2)}{f_q^-(x_1)}\right] = \mathrm{sign}\left[\frac{f_q(x_2)}{f_q(x_1)} - \frac{f_{\bar{q}}(x_2)}{f_{\bar{q}}(x_1)}\right]\,, \qquad x_1 > x_2$$

at high mass, no hierarchy between x_1 and x_2

- sign of the antisymmetric luminosity, and thus of forward-backward asymmetry, is the **relative rate of decrease of the quark and antiquark**, or valence and total quark PDFs, rather than their sign.
- Quantified by the effective asymptotic exponents, which illustrate richer structure in NNPDF4.0

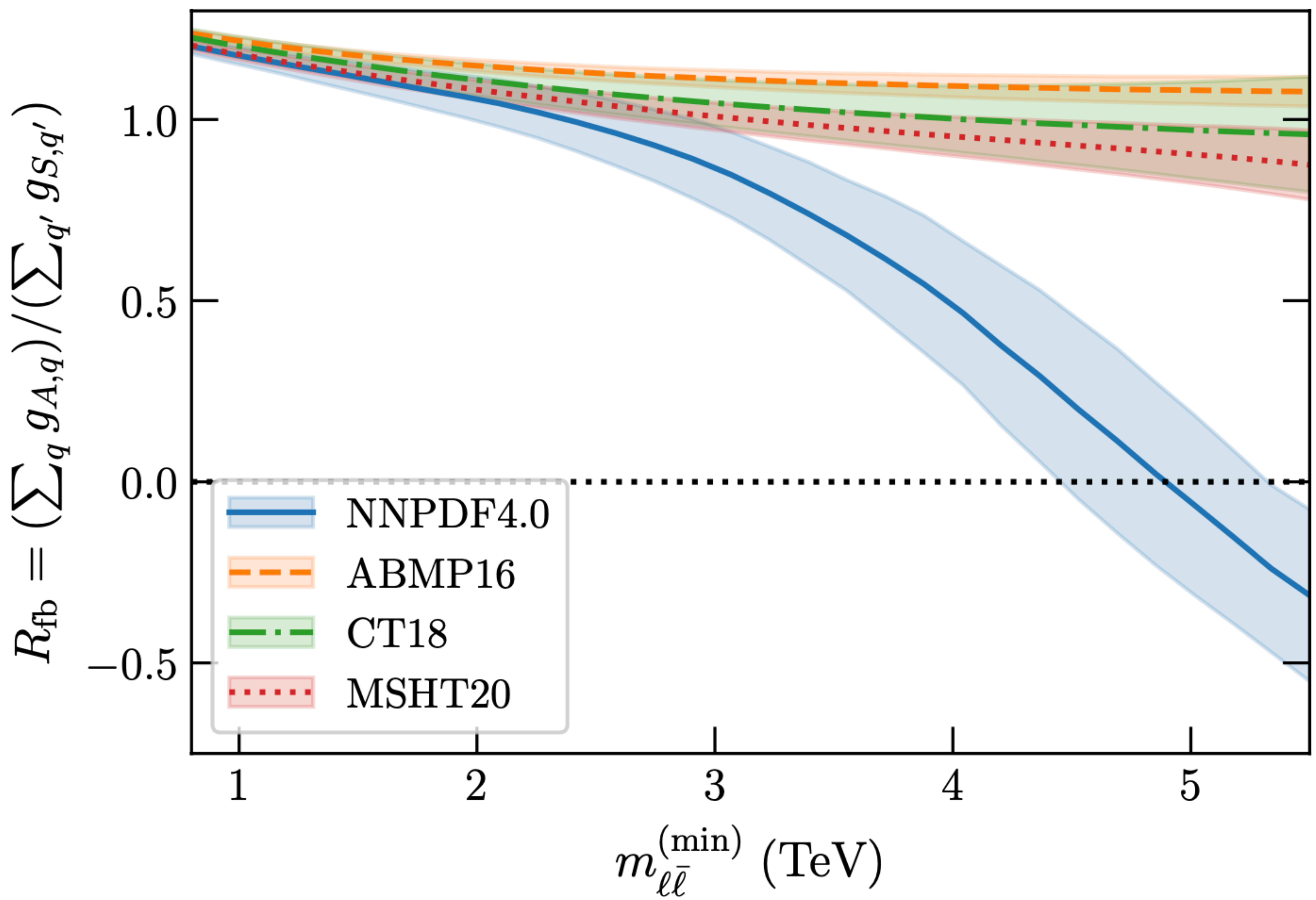


$$\beta_{a,q}(x,Q) \equiv \frac{\partial \ln |x f_q(x,Q)|}{\partial \ln(1-x)}$$

Positive or negative asymmetry?

- Evaluate the **PDF-dependent coefficient** of the forward-backward asymmetry in LO QCD:

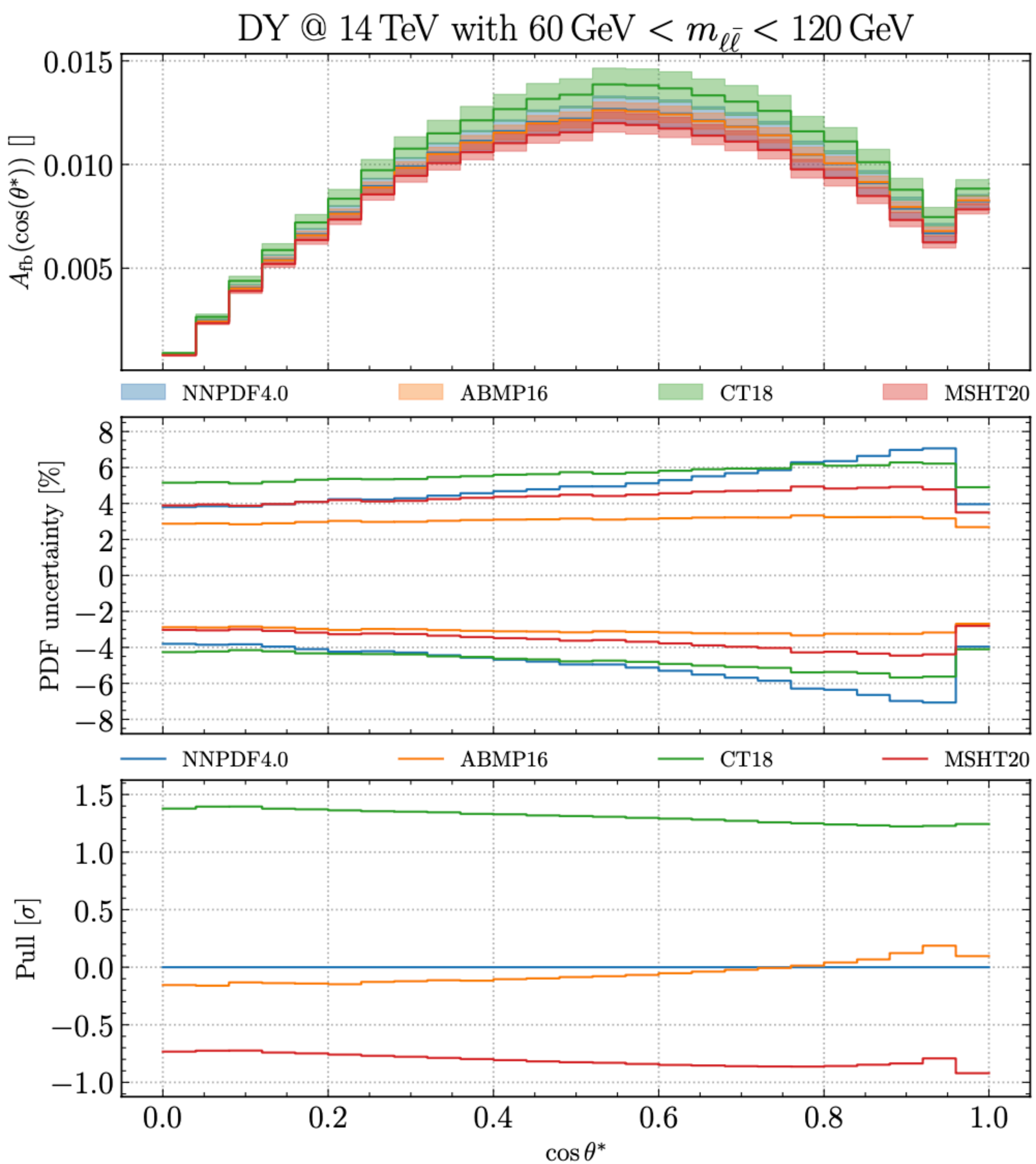
$$\frac{d\sigma}{d\cos\theta^*} = (1+\cos^2\theta^*)\sum_q g_{S,q} + \cos\theta^* \sum_q g_{A,q}$$



Prediction: for NNPDF4.0 the **forward-backward asymmetry eventually vanishes** at high masses, for the other groups the predictions are mass-independent

LHC phenomenology

- Validate our LO interpretation with realistic LHC simulations based on **mg5_aMC with NLO QCD and EW corrections** and with same fiducial selection cuts as in the ATLAS/CMS measurements

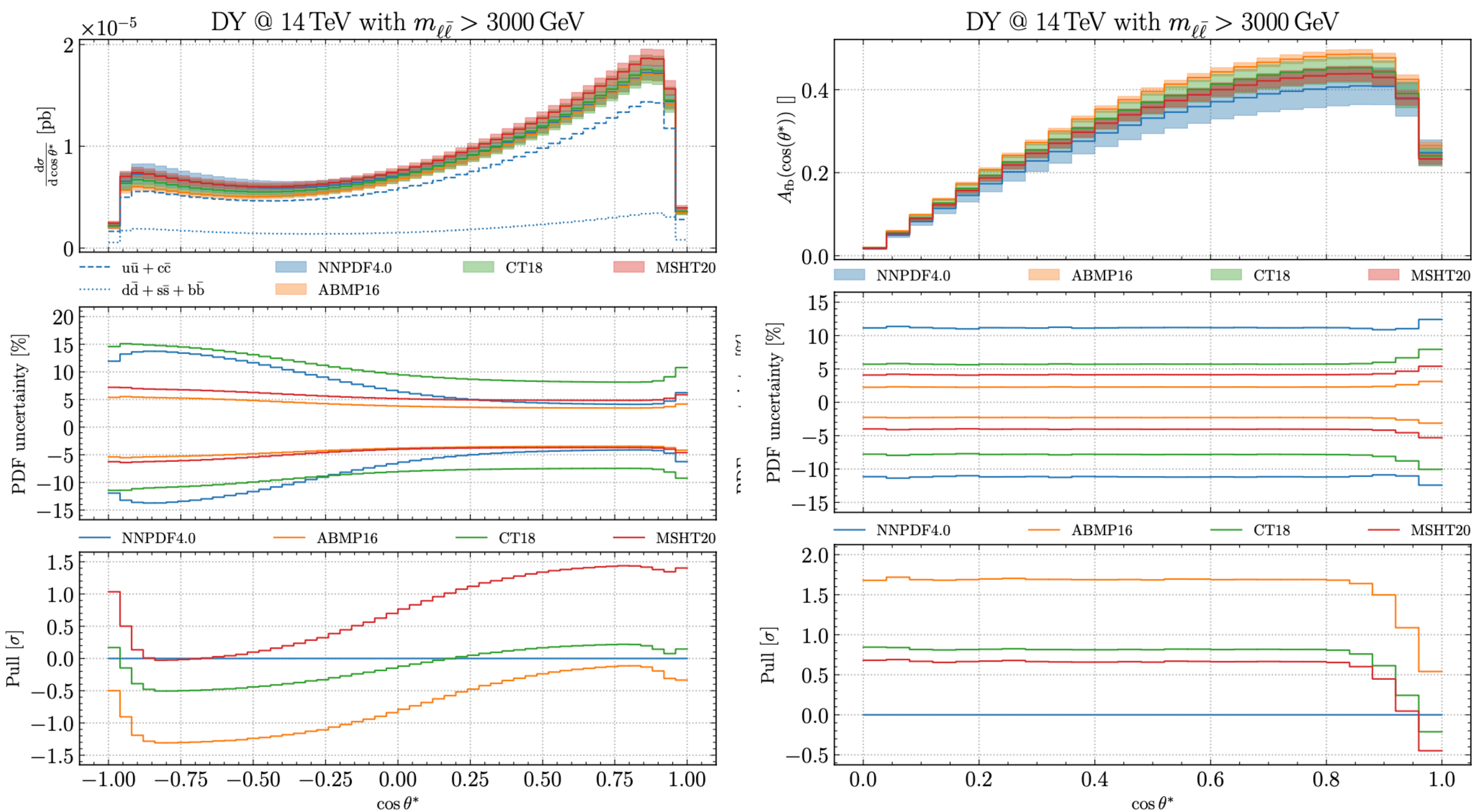


- As well known, **clearly positive FB asymmetry** with good agreement between PDF fits

- What happens at higher dilepton masses?

LHC phenomenology

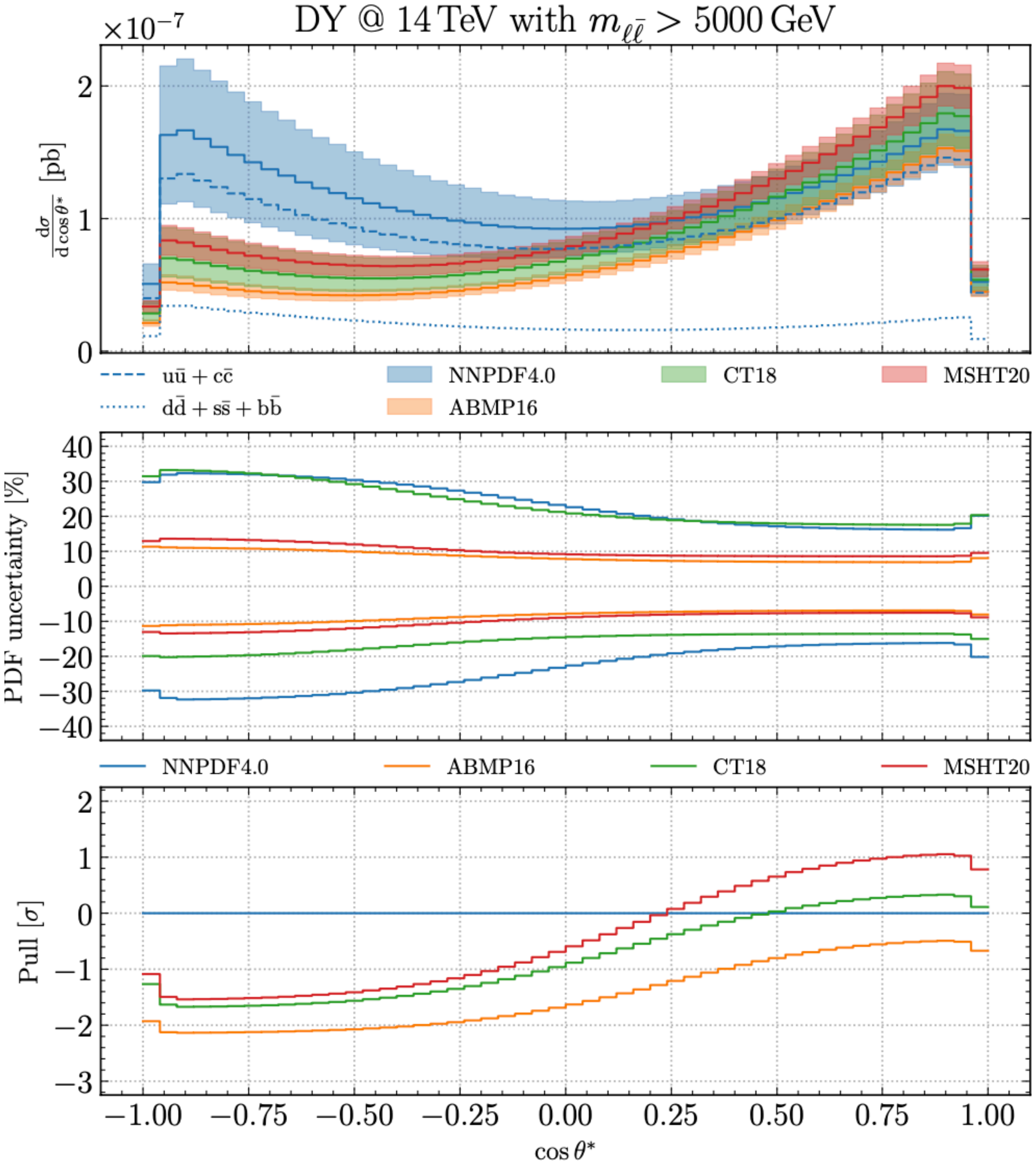
- For **dilepton masses > 3 TeV**, same qualitative behaviour, with clearly positive ***A***

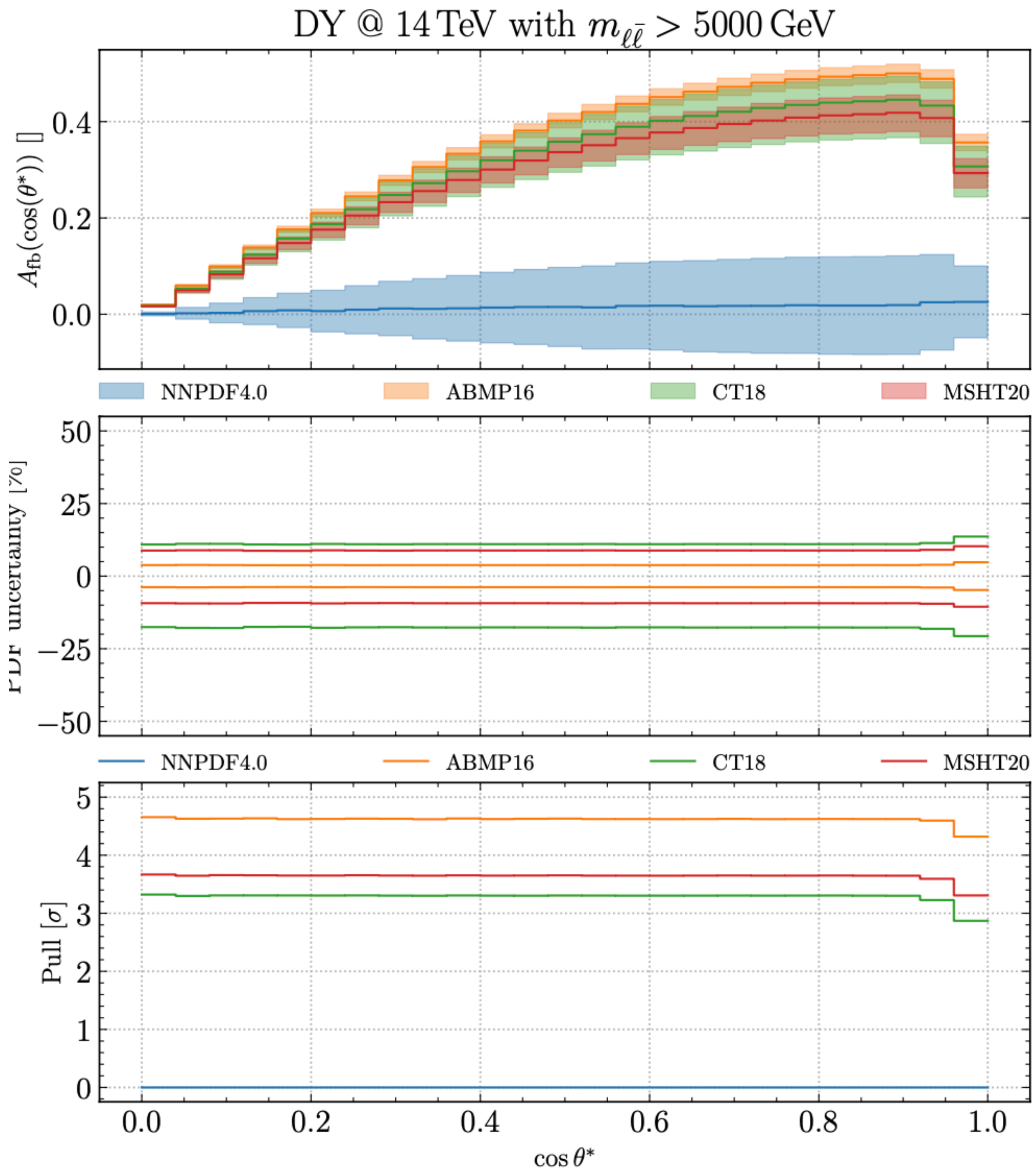


However, we know from the LO analysis that extrapolation to yet high masses may change the qualitative behaviour

LHC phenomenology

- For dilepton masses > 5 TeV, A_{FB} vanishes for NNPDF4.0, while other groups extrapolate





PDF uncertainties differ between PDF groups, with NNPDF4.0 displaying the largest ones

Summary

- As opposed to common lore, the forward-backward asymmetry in neutral-current Drell-Yan is **not positive-definite in the Standard Model**

- Explained by the behaviour of the **antisymmetric parton luminosities,** which probe features of the large-x PDFs not accessible with processes such as DY rapidity distributions

- Extrapolation to the large-x region of PDFs (and uncertainties) depends on **methodological assumptions** carried by PDF groups and on how much **large-*x* data considered**

- Our findings emphasise that a careful understanding of large-x PDFs is crucial in order to robustly **search for BSM physics in the high-mass region** …

- … and also that forward-backward asymmetry (or in general, triple-differential DY cross-sections) measurements at high mass provide **unique sensitivity to large-*x* PDFs**

Motivates taking a fresh look at other high-mass processes sensitive to both PDFs and BSM, from jets to top quark pair production